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Removal of trimethoprim and 5-fluorouracil by UV/persulfate and UV/VUV persulfate methods

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Abstract: The UV, UV/VUV photolysis and their combination with persulfate ($S_2O_8^{2-}$) were studied for the elimination of trimethoprim and 5-fluorouracil. Methods were examined in terms of transformation and mineralization rate, and the matrix effect. The relative contribution of the direct UV photolysis, and radical based reactions ($^{\bullet}OH$, $SO_4^{\bullet-}$) were also investigated. Without $S_2O_8^{2-}$, the efficiency of UV/VUV photolysis highly exceeds that of UV photolysis due to the $^{\bullet}OH$ formation, while in the presence of $S_2O_8^{2-}$, the dominant reaction partner is $SO_4^{\bullet-}$. However, $SO_4^{\bullet-}$ based methods proved to be efficient for both transformation and mineralization, they are sensitive for the matrix components.

Keywords: antibiotics, pharmaceuticals, wastewater, persulfate, energy consumption.

1. Introduction

The complete removal of pharmaceutical ingredients from waters is one of the most challenging tasks in water purification today. The application of antibiotics remains the primary treatment for bacterial infections for humans and animals. However, the excess of pharmaceuticals, especially antibiotics into the environment has led to the emergence of antibiotic-resistant bacterial strains and created a global health emergency causing at least 700,000 deaths a year. Besides antibiotics, we must also pay attention to removing other drugs used in large quantities but are difficult to biodegrade. The conventional wastewater treatment renders limited results in pharmaceuticals elimination; thus, additive water treatment processes are required to prevent their exceed into the environment and decrease the risk. Advanced Oxidation Processes (AOPs) are additional water treatment methods that use chemical or photochemical processes to decompose compounds that are not or only slightly removed by biological water treatment. Most AOPs are based on the highly reactive hydroxyl radical ($HO^{\bullet}$) generation; however, during the last decade, the number of publications relating to the investigation of chlorine species or sulfate radical ion-based processes has been fluently increasing.

The low-pressure mercury vapor (LPM) lamp emitting at 254 nm is a widely used light source for water disinfection, but its effectiveness in eliminating organic pollutants and reducing toxicity is highly limited. The molar absorbance at 254 nm and the quantum yield of the transformation of the target compound determine the efficiency of UV photolysis. The LPM lamps, equipped with special high-purity quartz, emit at 254 and 185 nm, and are suitable for high-purity water production due to the $HO^{\bullet}$ via absorption 185 nm VUV light by water:

$$H_2O + h\nu \rightarrow H^{\bullet} + HO^{\bullet}. \qquad \Phi(HO^{\bullet})_{185nm} = 0.33 \tag{1}$$

The efficacy of UV photolysis can be enhanced by using various oxidizing agencies, such as ozone, hydrogen peroxide, or persulfate ion [1]. During persulfate-based processes, the reaction with sulfate radical ions ($SO_4^{\bullet-}$) is the primary degradation pathway. Persulfate ($S_2O_8^{2-}$) is a strong oxidant but can be activated to generate highly reactive $SO_4^{\bullet-}$ characterized by a higher oxidative potential ($E^0 = 2.6$ V) than that of $S_2O_8^{2-}$ ($E^0 = 2.1$ V). The 254 nm UV light-activated persulfate ($S_2O_8^{2-}$; $\varepsilon254$ nm = 20-22 M^{-1} cm^{-1} [2])is a clean source for producing $SO_4^{\bullet-}$ with high quantum yield [2] via the homolytic bond cleavage [3]:

$$S_2O_8^{2-} + h\nu \rightarrow 2\ SO_4^{\bullet-}. \qquad \Phi(SO_4^{\bullet-})_{254nm} = 1.4 \pm 0.3 \tag{2}$$

The $SO_4^{\bullet-}$ is a potent oxidizing agent similar to the $HO^{\bullet}$ ($E^0 = 2.8$ V) [3]. The primary reaction mechanism of $SO_4^{\bullet-}$ initiated transformation of organic substances is the electron transfer opposite to the addition, which is characteristic of $HO^{\bullet}$ initiated transformations [4]. Based on the literature so far, the AOP methods based on $SO_4^{\bullet-}$ are adequate for the degradation and mineralization of organic micropollutants similar to $HO^{\bullet}$ based methods [5,6], especially in the case of the aromatic molecules with an amino group [7]. Comparing the primary reactive radicals, $HO^{\bullet}$ is less selective and more reactive towards saturated organic substances than $SO_4^{\bullet-}$. The reaction rate constants of $HO^{\bullet}$ with TRIM and 5-FU are 7.36×10^9 $M^{-1}s^{-1}$ [8] and 1.52×10^9 $M^{-1}s^{-1}$ [9], respectively, whereas the reaction rate constant with $SO_4^{\bullet-}$ is only available for TRIM, its value is 3.81×10^9 $M^{-1}s^{-1}$ [10], just slightly lower than with $HO^{\bullet}$.

This research compares and studies the UV photolysis, UV/VUV photolysis producing $HO^{\bullet}$, and their combinations with persulfate to eliminate and mineralize two commonly used pharmaceuticals, namely trimethoprim (TRIM), an antibiotic drug, and the 5-fluorouracil (5-FU), a chemotherapeutic agent. Both selected model components are present in detectable concentrations in urban and hospital wastewater [11,12].

2. Materials and methods

2.1. Photochemical experiments

Two low-pressure mercury vapor (LPM^{UV} and LMP^{VUV}) lamps were used as light sources. LPM^{UV} emits 254 nm UV photons (GCL307T5L/CELL, produced by LightTech), while LPM^{VUV} (GCL307T5VH/CELL produced by LightTech) emits both 254 nm UV and 185 nm VUV photons. Both lamps having the same electric (15 W) and geometric (227 mm arc length and 20,5 mm diameter) parameters. The envelope of LMP^{VUV} lamp was made from synthetic quartz to transmit the VUV_{185nm} photons. The UV photon flux was determined by ferrioxalate actinometry and found to be the same (3.70×10^{-6} mol_{photon} s^{-1}) for both LPM lamps. The flux of the 185 nm VUV photons was determined by methanol actinometry and found to be one magnitude lower; 3.23×10^{-7} mol_{photon} s^{-1}. The experiments were carried out in a 500 mL cylindrical glass reactor with a 45 mm inner diameter and 300 mm height. The thickness of the irradiated water layer was 13 mm, which is enough for the complete absorption of 185 nm photons [13]. The initial concentration of TRIM and 5-FU was 1.0×10^{-4} M in each case.

2.2. Materials and methods

The concentration of model compounds was performed by Agilent 1100 HPLC system, equipped with a diode array detector (DAD). For the analysis of TRIM (≥99%, Sigma-Aldrich) and its degradation products, Gemini 3u C6-phenyl 110A column was used (thermostated at 40 °C). The eluent contains 10% methanol (HPLC grade, VWR) and 90% formate buffer (≥99%, Sigma-Aldrich); the flow rate was 0.4 mL min^{-1}. In the case of 5-FU (≥99%, Sigma-Aldrich), the eluent consisted of 5.0×10^{-3} M sulfuric acid (HPLC grade, FLUKA), the flow rate was 0.8 mL min^{-1}. The detection wavelength was 275 nm for TRIM and 210 nm for 5-FU.

Total organic carbon (TOC) measurements were performed using an Analytik Jena N/C 3100 analyzer. For the investigation of matrix effect, biologically treated wastewater was used with high ionic ($c(HCO_3^-) = 526$ mg L^{-1} and $c(Cl^-) = 120$ mg L^{-1}) and relatively low organic content (TOC = 5–6 mg L^{-1}).

3. Results and discussion

3.1. UV and UV/VUV photolysis

The efficiency of direct photolysis is determined by the molar absorbance of the target substance at 254 nm and the quantum efficiency of the transformation. However, the molar absorbances of the model compounds have a similar value (4045 M^{-1} cm^{-1} for TRIM and 5297 M^{-1} cm^{-1} for 5-FU), the transformation of 5-FU is significantly higher no more than 10 minutes required for the complete removal in both O_2-free and O_2 containing solutions. There is practically no transformation of TRIM in O_2-free solution, and its transformation starts with a long induction period in O_2-containing one.

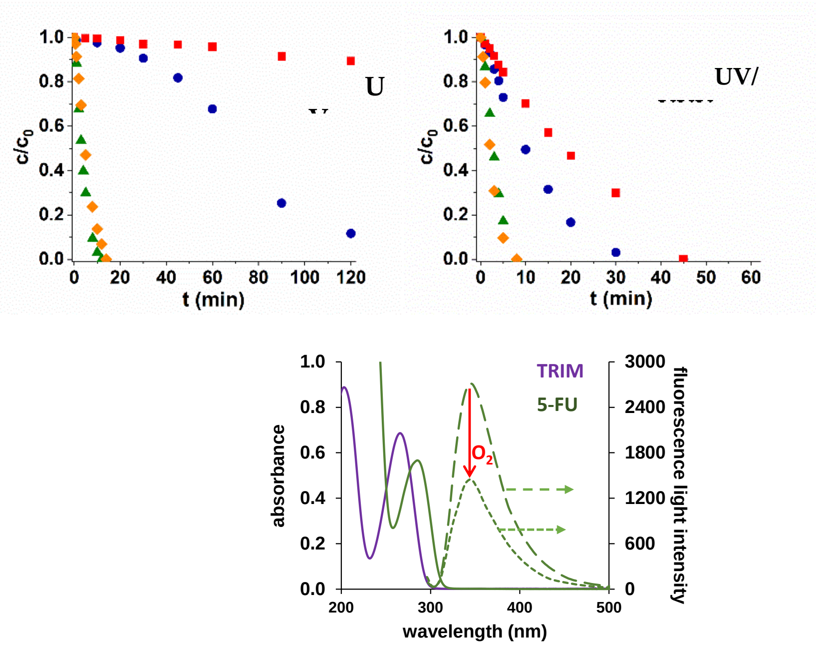
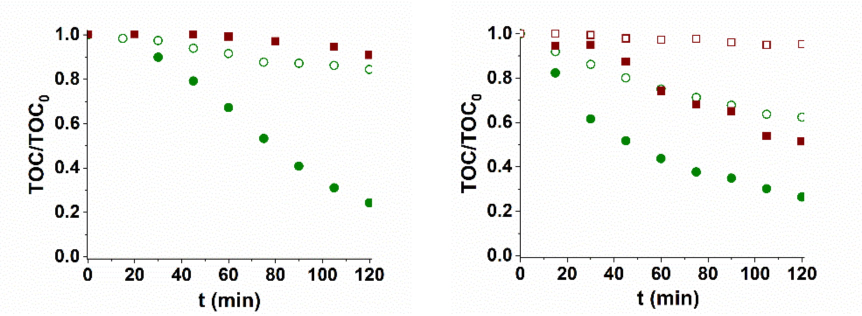


Figure 1. Degradation of TRIM and 5-FU during UV (a) and UV/VUV (b) photolysis and their absorption and emission spectra in O_2-free and O_2 containing solutions (c) (**●TRIM, air; ■TRIM, N_2; ▲5-FU, air; ◆5-FU, N_2**).

The fluorescence behavior of the compounds was investigated using 254 nm as excitation wavelength. For 5-FU no fluorescence was observed, while TRIM emitted an intensive fluorescent light with a maximum intensity at 340 nm. Thus, a significant part of the absorbed photons results in fluorescent light without chemical transformation. Consequently, the quantum yield related to the TRIM transformation is much lower (<0.002), than to the 5-FU transformation (0.08 and 0.061 in aerated and in O_2-free solutions, respectively). The dissolved O_2 decreased the intensity of fluorescent light, suggesting that O_2 can quench the excited state of TRM. The formed singlet oxygen is probably responsible for the positive effect of the dissolved O_2 on the transformation of TRIM in the case of UV photolysis.

In the case of UV/VUV photolysis, the low intensity 185 nm photons highly enhanced the transformation rate of TRIM both in aerated and O_2-free solutions due to the formation of reactive $H^\bullet$ and $HO^\bullet$ (1), but only slightly affected the 5-FU transformation (Fig. 1a and b). The manifestation of the degree of the positive effect of VUV photons depends on the relative contribution of direct UV photolysis and radical (mainly $HO^\bullet$) based transformation. For 5-FU the contribution of direct UV photolysis remains significant even in the presence of VUV light generated radicals, while for TRIM, the radical-based transformation became the primary way.

The presence of radicals produced by VUV photolysis of water also enhanced the mineralization rate. For TRIM, there is no observable mineralization in UV radiated solution, while 40% of TOC can be removed for 5-FU (Fig 2). In UV/VUV light irradiated O_2-containing solutions about 80% of TOC was removed during 2 h. The results also showed that dissolved O_2 has essential role in mineralization most probably because of the formation organic peroxyl radicals (Fig 2).

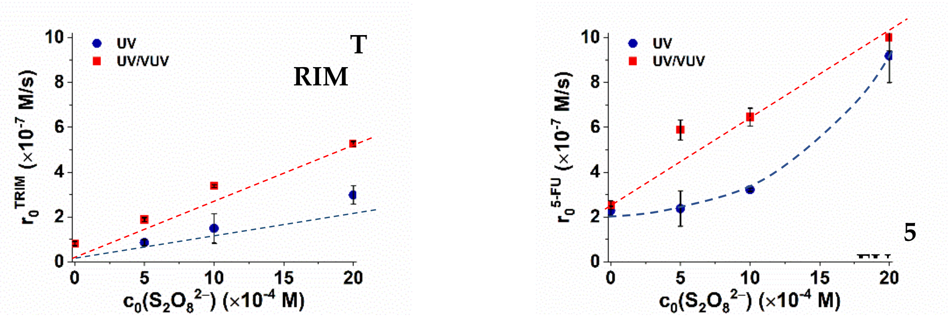


(a) (b)

Figure 2. Mineralization of TRIM (a) and 5-FU (b) during UV and UV/VUV photolysis (**■UV, air; □ UV, N_2;● UV/VUV, air; ○UV/VUV, N_2**).

3.2. Effect of $S_2O_8^{2-}$

In the case of both pharmaceuticals and light sources the $S_2O_8^{2-}$ addition enhanced the transformation rate independently on the presence of dissolved O_2, due to the formation of reactive $SO_4^{\bullet -}$ via UV photolysis of $S_2O_8^{2-}$.



(a) (b)

Figure 3. Effect of $S_2O_8^{2-}$ dosage on the degradation of TRIM (a) and 5-FU (b) in the case of UV and UV/VUV photolysis.

In the case of UV/$S_2O_8^{2-}$ process the transformation of organic substances can take place via direct UV photolysis or due to the reaction with $SO_4^{\bullet -}$. For UV/VUV/$S_2O_8^{2-}$, additionally, the reactions with $HO^\bullet$ must be taken into consideration. Comparing the molar absorbance of TRIM (4045 M^{-1} cm^{-1}), 5-FU (5297 M^{-1} cm^{-1}) and $S_2O_8^{2-}$ (30 M^{-1} cm^{-1}) the contribution of direct photolysis is probably remain significant for 5-FU and negligible for TRIM transformation besides $SO_4^{\bullet -}$ and/or $HO^\bullet$ initiated reactions at the given concentrations. Except in the case of UV/$S_2O_8^{2-}$ process for 5-FU elimination, the transformation rate increased linearly with the initial concentration of added $S_2O_8^{2-}$. In the case of UV/$S_2O_8^{2-}$ process for 5-FU elimination the transformation rate changes exponentially. (Fig. 3.)

For UV/VUV/$S_2O_8^{2-}$ the transformation rates are higher (approximately doubled) than for UV/$S_2O_8^{2-}$ process, which suggest that, the additive effect due to the VUV light is probably remained important even in the presence of $SO_4^{\bullet -}$. The primary reaction mechanism of $SO_4^{\bullet -}$ initiated transformation of organic substances (S) is the electron transfer, which results in SO_4^-. In VUV irradiated solutions water is the main absorbent because of its high concentration (55 M). But absorbance of SO_4^- is not negligible (ε_{185nm} = 160 M-1 cm^{-1}) and gives possibility for the VUV photolysis of SO_4^-, regenerating the $SO_4^{\bullet -}$ [14], with a relatively high quantum yield.

$$SO_4^{\bullet -} + S \rightarrow SO_4^- + S^{\bullet -} \quad (3)$$

$$SO_4^{2-} + h\nu_{185nm} \rightarrow SO_4^{\bullet -} + e_{aq}^- \qquad \Phi(SO_4^{\bullet -})_{185nm} = 0.64 \quad (4)$$

Table 1. The initial transformation rate of TRIM and 5-FU using various processes ($c(S_2O_8^{2-}) = 1.0\times10^{-3}$ M).

process	$r_0(\times10^{-7}$ M $s^{-1})$ TRIM	$r_0(\times10^{-7}$ M $s^{-1})$ 5-FU
UV/air	–	2.28
UV/N_2	–	1.54
UV/air/$S_2O_8^{2-}$	1.49	3.22
UV/N_2/$S_2O_8^{2-}$	1.39	4.23
UV/VUV/air	0.82	2.53
UV/VUV/N_2	0.50	3.92
UV/VUV/air/$S_2O_8^{2-}$	3.38	6.45
UV/VUV/N_2/$S_2O_8^{2-}$	3.28	7.12

In many cases, the intermediates formed in the transformation of pharmaceuticals still have biological activity, so it is particularly important to study not only the conversion of the parent compound but also its mineralization. The mineralization was investigated with three different $S_2O_8^{2-}$ concentrations. Both dissolved O_2 and $S_2O_8^{2-}$ enhanced the mineralization rate. The additive positive effect of VUV light is well manifested not only for transformation but also for mineralization efficiency. Using UV radiation the mineralization rate increased with $S_2O_8^{2-}$ concentration, but in UV/VUV irradiated solutions it was practically independent on that. At 1.0×10^{-3} M $S_2O_8^{2-}$ concentration, using UV radiation, the mineralization efficiency is close to that measured in UV/VUV photolysis.

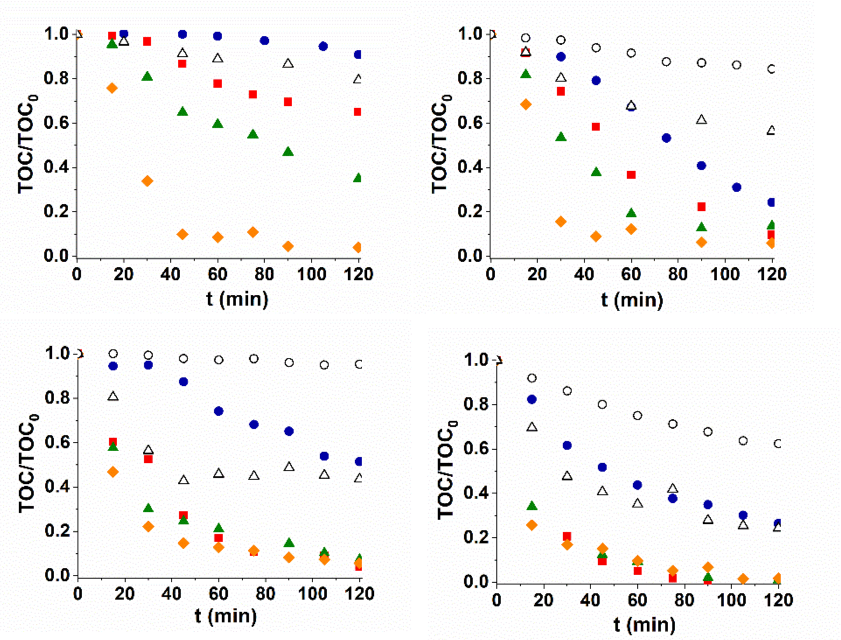


Figure 4. Mineralization of TRIM (a,b) and 5-FU (c,d) during UV (a, c) and UV/VUV photolysis (b, d)(**●air; ○ N_2; ■5.0×10^{-4} M $S_2O_8^{2-}$, air; ▲1.0×10^{-3} M $S_2O_8^{2-}$, air; Δ 1.0×10^{-3} M $S_2O_8^{2-}$, N_2;◆ 2.0×10^{-3} M $S_2O_8^{2-}$, air**).

3.3. Radical scavenger

The role of $HO^\bullet$ radical was investigated with a commonly used $HO^\bullet$ scavenger, tert-butanol (t-BuOH). The t-BuOH reacts 3 orders of magnitude faster with $HO^\bullet$ ($k_{HO^\bullet} = 6.0\times10^{8}$ $M^{-1}s^{-1}$) [15] than with $SO_4^{\bullet-}$ ($k_{SO_4^{\bullet-}} = 4.0\times10^{5}$ $M^{-1}s^{-1}$) [16]. Applying 3.0×10^{-2} M t-BuOH ensured that, 95% of $HO^\bullet$ and no more than 3% of $SO_4^{\bullet-}$ reacts with t-BuOH. At first, the effect of radical scavenger was investigated in the case of UV/VUV photolysis and found to be significant for TRIM, while for 5-FU the effect was moderated because of the relatively high contribution of the direct photolysis to the transformation. During $S_2O_8^{2-}$

based processes the t-BuOH just slightly inhibited the transformation, which means that the $SO_4^{\bullet-}$ is the dominant reaction partner. It also confirmed that, in the presence $S_2O_8^{2-}$ the positive effect of VUV is most probably attributable to the regeneration of $SO_4^{\bullet-}$ (4) and not to the $HO^{\bullet}$ formation, opposite to the simple UV/VUV photolysis.

Table 2. Effect of t-BuOH (3.0×10^{-2} M) on the degradation of TRIM and 5-FU.

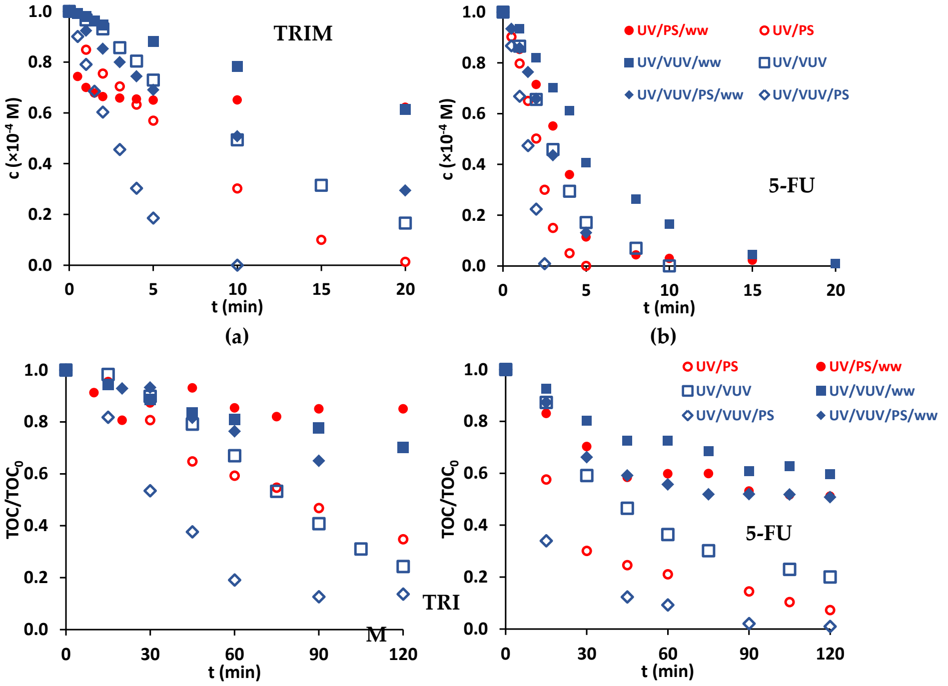
	r_0 ($\times 10^{-7}$ M/s)	
	TRIM	**5-FU**
UV	–	2.28
UV/$S_2O_8^{2-}$	1.49	3.22
UV/$S_2O_8^{2-}$/tBuOH	1.59	5.40
UV/VUV	0.82	2.53
UV/VUV/tBuOH	0.21	2.18
UV/VUV/$S_2O_8^{2-}$	3.38	6.45
UV/VUV/$S_2O_8^{2-}$/tBuOH	2.88	5.00

3.4. Matrix effect

In the development of additive water treatment processes, it is important to examine the effect of matrices and energy consumption because of several practical reasons. In this study, a biologically treated domestic wastewater was used, having low organic content (5–6 mg L^{-1}) and relatively high Cl^- (3.4×10^{-3} M) and HCO_3^- (8.6×10^{-3} M) concentration.

The biologically treated domestic wastewater has no significant absorbance at 254 nm, thus it has no effect on the UV photolysis. For UV/VUV photolysis the organic content and HCO_3^- behaves as $HO^{\bullet}$ scavenger ($k = 8.5 \times 10^6$ M^{-1} s^{-1}, [16]) and inhibited the transformation and mineralization. The effect of Cl^- is not completely clarified. It can reacts with $HO^{\bullet}$ ($k = 4.3 \times 10^9$ M^{-1} s^{-1}, [17]), but several studies described, that no significant radical scavenging effect of Cl^- because of the fast backward reaction.

The negative effect of matrix manifested well for UV/$S_2O_8^{2-}$ process. For TRIM the transformation and mineralization were completely inhibited after a short period, while in MilliQ water both were extremely fast. For 5-FU in terms of transformation, the effect is moderated, however, mineralization is inhibited similarly to TRIM. For UV/VUV/$S_2O_8^{2-}$ similar trends were observed, but the inhibitory effect of the matrix is less stronger than for UV/$S_2O_8^{2-}$.



(c) **(d)**

Figure 5. Effect of biologically treated domestic wastewater (ww) as matrix of the transformation (a, b) and mineralization (c, d) of TRIM (a, c) and 5-FU (b, d) ($c(S_2O_8^{2-}) = 1.0\times10^{-3}$ M).

For $S_2O_8^{2-}$ based processes the main reaction partner is $SO_4^{\bullet-}$. The $SO_4^{\bullet-}$ react moderately fast with both Cl^- ($k = 3.6\times10^8$ M^{-1} s^{-1}) and HCO_3^- ($k = 1.6\times10^6$ M^{-1} s^{-1}) via electron transfer reaction:

$$SO_4^{\bullet-} + Cl^- \rightarrow SO_4^- + Cl^\bullet \tag{5}$$

$$Cl^\bullet + Cl^- \rightarrow Cl_2^{\bullet-} \tag{6}$$

$$SO_4^{\bullet-} + HCO_3^- \rightarrow SO_4^{2-} + CO_3^{\bullet-} + H^+ \tag{7}$$

The further transformation of $Cl_2^{\bullet-}$ can finally results in $HO^\bullet$ at neutral pH from $Cl^\bullet$/ $Cl_2^{\bullet-}$ reaction with water. The formed $CO_3^{\bullet-}$ is a quite selective reactive species, its reaction rate constant with TRIM is 1.3×10^7 M^{-1} s^{-1} [18]. By increasing the concentration of persulfate, good efficiency can be obtained even in such a complex matrix, as the biologically treated wastewater. The required PDS concentration is determined by the analytical parameters of the matrix, especially the TOC content, and the inorganic ion concentration.

4. Conclusions

In this work, UV (254 nm) and UV/VUV (254 and 185 nm) photolysis was combined with persulfate ($S_2O_8^{2-}$) addition. Trimethoprim (TRIM) and 5-fluorouracil (5-FU), commonly used drugs were used as target substances. Opposite to the similar molar absorbances, UV photolysis was effective only for 5-FU transformation, while the low intensity VUV photons enhanced the transformation and mineralization rates of both components. Addition of $S_2O_8^{2-}$ highly enhanced the transformation and mineralization efficiencies, linearly with $S_2O_8^{2-}$ concentration. The effect of t-BuOH as radical scavenger proved that the main reaction partner the $SO_4^{\bullet-}$ even in the case of the UV/VUV/$S_2O_8^{2-}$ process. In biologically treated domestic wastewater as matrix, the efficacy of UV/$S_2O_8^{2-}$ and UV/VUV/$S_2O_8^{2-}$ processes are significantly reduced partly due to the organic matter and mainly due to the reaction of $SO_4^{\bullet-}$ with inorganic ions.

Author Contributions: Luca Farkas: experimental work, writing—original draft preparation; Adrienn Szirmai and Anett Covic: experimental work; Tünde Alapi: conceptualization, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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